REMARKS

In the Office Action dated October 20, 2004, claim 1 was rejected under 35 U.S.C. §102(b) as being anticipated by Kuroiwa et al. Claim 5 was rejected under 35 U.S.C. §103(a) as being unpatentable over Kuroiwa et al.

Claims 2-4 were stated to be allowable if rewritten in independent form. The rejection of claim 1 (as well as the rejection of claim 5) is respectfully traversed, and therefore claims 2-4 have been retained in dependent form at this time.

In the subject matter disclosed and claimed in the present application, a venturi-type flow meter and a hot wire flow meter are used to measure the flow of the same gas flow. The venturi-type flow meter produces an output signal, and the hot wire flow meter also produces an output signal, that is separate from the output of the venturi-type flow meter. These two signals are supplied to a measurement system that determines a gas flow rate from these outputs.

The Kuroiwa et al reference, by contrast, makes use of a specific type of flow meter, known as a Karman vortex flow meter. This is a well-known type of flow meter, and attached hereto as examples describing the basic operation of this known type of flow meter are United States Patent No. 5,005,427 and an excerpt from the website entitled The Engineering Toolbox. In the '427 patent, the principles of operation of a Karman vortex flow meter are described beginning at column 1, line 32. In the Engineering Toolbox excerpt, these principles are described in the paragraph beginning at the bottom of page 7, below the heading "Vortex Flow Meters".

A Karman vortex flow meter has a double-venturi-structure that produces a so-called Karman stream by disposing a so-called bluff body in a stream of flowing fluid. The interaction of the flowing fluid with the bluff body produces a vortex, which

is subsequently "shed" downstream. A sensor is employed to detect the "shedding" of this vortex, from which a measurement of the flow is derived. Any suitable type of sensor can be used to measure this "shedding," including a hot wire sensor, and ultrasound sensor, or any other suitable type.

Thus, in a Karman vortex flow meter, the output of the hot wire sensor (if that is, in fact, the type of sensor that is employed) forms the output of the Karman vortex flow meter itself. There is no separate venturi-type flow meter from which an output is also obtained, as in the subject matter disclosed and claimed in the present application. As explained at page 4 of the present specification, a venturi-type flow meter operates according to a completely different principle, namely based on equation (2) set forth on page 4.

In the Kuroiwa et al reference, two Karman vortex flow meters are used, and these each happen to employ a hot wire as the sensor. Because of their use within the respective Karman vortex sensors, however, the outputs of the hot wire sensors in the Kuroiwa et al sensor cannot be considered as an output of a hot wire flow meter, in the sense of claim 1 of the present application. Instead, the outputs of the flow meters in the Kuroiwa et al reference must be considered as Karman vortex flow meter outputs. Moreover, a separate output from a venturi-type flow meter does not exist in the Kuroiwa et al reference.

Claim 1 has been amended to make clear that the output of the venturi-type flow meter is separate from the output of the hot wire flow meter, and that both of these outputs are used to determine the flow. No such structure is disclosed in the Kuroiwa et al reference, and therefore that reference does not anticipate claim 1.

Consistent with the reasons discussed above in connection with claim 1, the subject matter of claim 5 would not have been obvious to a person of ordinary skill in

the field of flow meter design and construction based on the teachings of Kuroiwa et al. Since claim 5 explicitly requires that a difference value be formed between the output from the venturi-type flow meter and the output from the hot wire flow meter, it is essential that these respective flow meters produce respective separate signals, otherwise the formation of a "difference" between these signals would be meaningless. As noted above, although the Kuroiwa et al reference does, in fact, disclose two Karman vortex sensors, each of which produces an output signal, these signals are not respective signals from a venturi-type flow meter and a hot wire flow meter, as required in claim 5. Moreover, the passage at column 4, lines 17-30 in the Kuroiwa et al reference explicitly states that the switching circuit 11 supplies one or the other of these signals to the shaper circuit 12. There is no teaching or suggestion (and no need) in the Kuroiwa et al reference to form a difference between these signals, nor to compare that difference to a threshold level. Forming a difference between those signals would preclude the described operation of the switching circuit 11 in Kuroiwa et al above supplying one or the other of these signals to the shaper circuit 12.

Therefore, a person of ordinary skill in the field of flow meter design and construction would find no teaching, guidance, motivation or inducement in the Kuroiwa et al reference to modify that reference to form a difference between the two output signals from the respective Karman vortex meters, and then to compare that difference to a threshold, as set forth in claim 5.

All claims of the application are therefore submitted to be in condition for allowance, and early reconsideration of the application is respectfully requested.

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I hereby certify that this correspondence is being deposited with the United States Postal Service as First Class mail in an envelope addressed to: Commissioner for Patents, P.O. Box 1450, Alexandria, Virginia 22313-1450 on December 28, 2004.

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Process Control - Instrumentation and process control systems ...

Fluid Flowmeters - Flow metering basics. Introduction to Orifice, Venturi, Flow Nozzles, Pitot Tubes, Target, Displacement, Turbine, Vortex, Electromagnetic, Ultrasonic Doppler, Ultrasonic Time-of-travel, Mass Coriolis, Mass Therma and Sluice Gate flow meters.

Flowmeters and Turndown Ratio

An introduction to turndown ratio for flow measurement devices as orifices, venturi meter etc. .

Electromagnetic Flowmeters

An introduction to electromagnetic flowmeters and their principles .

Flowmeters and Accuracy

An introduction to accuracy in flow measurement devices .

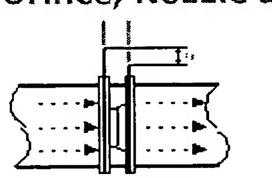
Flowmeters Selection Guide

A guide to select between the different fluid flowmeter principles available regarding service, rangeability, pr accuracy, upstream pipe diameters, viscosity and relative costs .

Fluid Mechanics

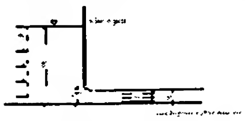
The study of fluids - liquids and gases, involves various properties of the fluid, such as velocity, pressure, de functions of space and time .

Orifice, Nozzle and Venturi Flow Rate Meters



The orifice, nozzle and venturi flow rate meters use the Bernoulli Equation to calculate the pressure difference between an obstruction in the flow. .

- Pitot Tubes - Pitot tubes can be used to indicate fluid flow velocities by measuring static and dynamic pressures in fluids



- Sluice Gate Flow Measurements - Sluice gates are used for controlling and measuring flow rates ii mainly in connection to hydro power plants .
- Target Flow Meters - An introduction to the target flow meters principles .
- Types of Fluid Flow Meters - An introduction to different types of fluid flowmeters - Orifices, Venturies, Nozzles, Rotamet Turbine, Vortex, Electromagnetic, Doppler, Ultrasonic, Thermal, Coriolis .
- U-Tube Manometer - The inclined and vertical u-tube manometer is inexpensive and common in differential pressure me and nozzles .
- Ultrasonic Doppler and Time of Flight Flowmeters - An basic introduction to the ultrasonic Doppler and Time of Flight Flo
- Ultrasonic Flowmeters - A basic tutorial to ultrasonic flowmeters .
- Viscosity Converting Chart - A dynamic viscosity converting chart for units as Poiseuille - Poise - centiPoise - kg/m.h- kg lbf.h/ft^2 - lb/ft.s - lb/ft.h .
- Vortex Flowmeters - An introduction to vortex flowmeters .
- Water Flow Measurements - A manual providing guidance in selecting, managing, inspecting, and maintaining water mea standard methods and devices commonly used to measure irrigation water .

- Weirs - Flow Measurement Standards - Standards of weir flow measurements .
- Weirs - V-Notch Flow Calculator - Flow rates in V-notch weirs can be calculated with this online calculator .
- Weirs and Flow Rate Measuring - Weirs are used for measuring flow rates in open channels and rivers - common in coni sewage plants .

Vortex Flowmeters

An introduction to vortex flowmeters

The Strouhal Number An introduction to and a definition of the Strouhal Number. .

Electronic Flowmeters

While the flow measurement technologies discussed in this chapter--magnetic, vortex, and ultrasonic--are neither exclusively nor exhaustively electronic in nature, they do represent a logical grouping of flow measurement technologies. All have no moving parts (well, maybe vibrating), are relatively non-intrusive, and are made possible by today's sophisticated electronics technology.

Magnetic flowmeters, for example, are the most directly electrical in nature, deriving their first principles of operation from Faraday's law. Vortex meters depend on piezoelectric sensors to detect vortices shed from a stationary shedder bar. And today's ultrasonic flowmeters owe their successful application to sophisticated digital signal processing.

Magnetic Flowmeters

The operation of magnetic flowmeters is based on Faraday's law of electromagnetic induction. Magmeters can detect the flow of conductive fluids only. Early magmeter designs required a minimum fluidic conductivity of 1-5 microsiemens per centimeter for their operation. The newer designs have reduced that requirement a hundredfold to between 0.05 and 0.1.

The magnetic flowmeter consists of a non-magnetic pipe lined with an insulating material. A pair of magnetic coils is situated as shown in Figure 4-1, and a pair of electrodes penetrates the pipe and its lining. If a conductive fluid flows through a pipe of diameter (D) through a magnetic field density (B) generated by the coils, the amount of voltage (E) developed across the electrodes--as predicted by Faraday's law--will be proportional to the velocity (V) of the liquid. Because the magnetic field density and the pipe diameter are fixed values, they can be combined into a calibration factor (K) and the equation reduces to:

The velocity differences at different points of the flow profile are compensated for by a signal-weighing factor. Compensation is also provided by shaping the magnetic coils such that the magnetic flux will be greatest where the signal weighing factor is lowest, and vice versa.

Manufacturers determine each magmeter's K factor by water calibration of each flowtube. The K value thus obtained is valid for any other conductive liquid and is linear over the entire flowmeter range. For this reason, flowtubes are usually calibrated at only one velocity. Magmeters can measure flow in both directions, as reversing direction will change the polarity but not

Figure 4-1: Click on figure to enlarge.

the magnitude of the signal.

The K value obtained by water testing might not be valid for non-Newtonian fluids (with velocity-dependent viscosity) or magnetic slurries (those containing magnetic particles). These types of

fluids can affect the density of the magnetic field in the tube. In-line calibration and special compensating designs should be considered for both of these fluids.

Magmeter Excitation

The voltage that develops at the electrodes is a millivolt signal. This signal is typically converted into a standard current (4-20 mA) or frequency output (0-10,000 Hz) at or near the flowtube. Intelligent magnetic transmitters with digital outputs allow direct connection to a distributed control system. Because the magmeter signal is a weak one, the lead wire should be shielded and twisted if the transmitter is remote.

The magmeter's coils can be powered by either alternating or direct current (Figure 4-2). When ac excitation is used, line voltage is applied to the magnetic coils. As a result, the flow signal (at constant flow) will also look like a sine wave. The amplitude of the wave is proportional to velocity. In addition to the flow signal, noise voltages can be induced in the electrode loop. Out-of-phase noise is easily filtered, but in-phase noise requires that the flow be stopped

Figure 4-2: Click on figure to enlarge.

(with the pipe full) and the transmitter output set to zero. The main problem with ac magmeter designs is that noise can vary with process conditions and frequent re-zeroing is required to maintain accuracy.

In dc excitation designs, a low frequency (7-30 Hz) dc pulse is used to excite the magnetic coils. When the coils are pulsed on (Figure 4-2), the transmitter reads both the flow and noise signals. In between pulses, the transmitter sees only the noise signal. Therefore, the noise can be continuously eliminated after each cycle.

This provides a stable zero and eliminates zero drift. In addition to being more accurate and able to measure lower flows, dc meters are less bulky, easier to install, use less energy, and have a lower cost of ownership than ac meters. One new dc design uses significantly more power than the earlier generations and thereby creates a stronger flowtube signal.

Another new design uses a unique dual excitation scheme that pulses the coils at 7 Hz for zero stability and also at 70 Hz to obtain a stronger signal. Magmeter transmitters can be supplied with either ac or dc power. A two-wire, loop-powered dc magnetic flowmeter is also available in an intrinsically safe design, but its performance is reduced because of power limitations.

Pulsed ac meters have also been introduced recently, eliminating the zero stability problems of traditional ac designs. These devices contain circuitry that periodically disrupts the ac power, automatically zeroing out the effects of process noise on the output signal.

Today, dc excitation is used in about 85% of installations and ac magmeters claim the other 15% when justified by the following conditions:

When air is entrained in large quantities in the process stream;

When the process stream is a slurry and the solid particle sizes are not uniform and/or the solid phase is not homogeneously mixed within the liquid; or

When the flow is pulsating at a frequency under 15 Hz.

When any of the above three conditions exist, the output of a pulsed dc meter is likely to be noisy. In some cases, one can minimize the noise problem (hold the fluctuations within 1% of

setpoint) by filtering and damping the output signal. If more than 1 to 3 seconds of damping is required to eliminate the noise, it is always better to use an ac meter.

Flowtubes, Liners, & Probes

The face-to-face dimensions of flanged flowtubes (lay lengths) usually meet the recommendations of the International Organization for Standardization (ISO). The dimensions of short-form magmeters usually meet these guidelines as well. Magnetic flowtubes and liners are available in many materials and are widely used in all the process industries, including food, pharmaceutical, mining, and metals.

Some liner materials (particularly Teflon®) can be damaged when pry bars are used while installing it or removing it from process piping. They can also be damaged by over-torquing the flange bolts. Liner protectors are available to help prevent such damage.

Any flowtube can generally be used with any transmitter offered by the same manufacturer. Depending on its construction and features, the cost of a 2-in. magnetic flowmeter can range from $1,500 to $5,000. This cost has been coming down, but is still higher than that of the least expensive flow sensors.

Magnetic flowmeters also can be packaged as probes and inserted into process pipes through taps. These probes contain both the electrodes and magnetic coils. The flowing process fluid induces a voltage at the electrodes, which reflects the velocity at the probe tip and not the average fluid velocity across the pipe. These magmeters are inexpensive and retractable. Therefore, the process does not have to be shut down to install or remove them. Metering accuracy is highly dependent on the relationship between the measured velocity and the average velocity in the pipe.

Electrodes

In conventional flowtubes, the electrodes are in contact with the process fluid. They can be removable or permanent if produced by a droplet of liquid platinum as it sinters through a ceramic liner and fuses with the aluminum oxide to form a perfect seal. This design is preferred due to its low cost, its resistance to abrasion and wear, its insensitivity to nuclear radiation, and its suitability for sanitary applications because there are no cavities in which bacteria can grow. On the other hand, the ceramic tube cannot tolerate bending, tension, or sudden cooling and cannot handle oxidizing acids or hot and concentrated caustic.

Figure 4-3: Click on figure to enlarge.

In a more recent capacitively- coupled design, non-contacting electrodes are used. These designs use areas of metal sandwiched between layers of liner material. They are available in sizes under eight inches in diameter and with ceramic liners. Magmeters using these non-contacting electrodes can "read" fluids having 100 times less conductivity than required to actuate conventional flowtubes. Because the electrode is behind the liner, these designs are also better suited for severe coating applications.

Recent Developments

When a magnetic flowmeter is provided with a capacitance level sensor embedded in the liner, it can also measure the flow in partially full pipes. In this design, the magmeter electrodes are located at the bottom of the tube (at approximately 1/10 the pipe diameter) in order to remain covered by the fluid. Compensation is provided for wave action and calibration is provided for full pipe, no flow (static level), and partially filled pipe operation.

Another recent development is a magnetic flowmeter with an unlined carbon steel flowtube. In this design, the measuring electrodes mount externally to the unlined flowtube and the magnetic coils generate a field 15 times stronger than in a conventional tube. This magnetic field penetrates deep into the process fluid (not just around the electrode as with standard magmeter probes). The main advantage is low initial and replacement costs, since only the sensors need be replaced.

Selection & Sizing

Magnetic flowmeters can detect the flow of clean, multi-phase, dirty, corrosive, erosive, or viscous liquids and slurries as long as their conductivity exceeds the minimum required for the particular design. The expected inaccuracy and rangeability of the better designs are from 0.2-1% of rate, over a range of 10:1 to 30:1, if the flow velocity exceeds 1 ft/sec. At slower flow velocities (even below 0.1 ft/s), measurement error increases, but the readings remain repeatable.

It is important that the conductivity of the process fluid be uniform. If two fluids are mixed and the conductivity of one additive is significantly different from that of the other process fluid, it is important that they be completely intermixed before the blend reaches the magmeter. If the blend is not uniform, the output signal will be noisy. To prevent that, pockets of varying conductivity can be eliminated by installing a static mixer upstream of the magmeter.

Magmeter size is determined by capacity tables or charts published by the manufacturer. Figure 4-3 provides a flow capacity nomograph for line sizes from 0.1 in. to 96 in. For most applications, flow velocities should fall between 3 ft/sec and 15 ft/sec. For corrosive fluids, the normal velocity range should be 3-6 ft/sec. If the flowtube is continuously operated below 3 ft/sec, metering accuracy will deteriorate, while continuous operation exceeding the upper limit of the normal velocity range will shorten the life of the meter.

The obstructionless nature of the magmeter lowers the likelihood of plugging and limits the unrecovered head loss to that of an equivalent length of straight pipe. The low pressure drop is desirable because it lowers pumping costs and aids gravity feed systems.

Problem Applications

The magmeter cannot distinguish entrained air from the process fluid; therefore, air bubbles will cause the magmeter to read high. If the trapped air is not homogeneously dispersed, but takes the form of air slugs or large air bubbles (the size of the electrode), this will make the output signal noisy or even disrupt it. Therefore, in applications where air entrainment is likely, the meter should be sized so that the flow velocity under normal flow conditions is 6-12 ft/sec.

Coating of the electrodes is another common magmeter problem. Material build-up on the inner surfaces of the meter can electrically isolate the electrodes from the process

Figure 4-4: Click on figure to enlarge.

fluid. This can cause a loss of signal or a measurement error, either by changing the diameter of the flowtube or by causing span and zero shifts. Naturally, the best solution is prevention. One preventive step is to size the meter such that, under normal flow conditions, the flowing velocity will be relatively high: at least 6-12 ft/sec, or as high as practical considering the possibility of erosion and corrosion.

Another method of prevention is to use electrodes that protrude into the flow stream to take

advantage of the turbulence and washing effect. In more severe service, a mechanical cleaning system can be installed and used intermittently or continuously to eliminate coating and build-ups.

Installation

The magnetic flowmeter must always be full of liquid. Therefore, the preferred location for magmeters is in vertical upward flow lines. Installation in horizontal lines is acceptable if the pipe section is at a low point and if the electrodes are not at the top of the pipe. This prevents air from coming into contact with the electrodes. When the process fluid is a slurry and the magmeter is installed at a low point, it should be removed during long periods of shutdown, so that solids will not settle and coat the internals.

If it is essential to drain the magmeter periodically, it should be provided with an empty tube zero option. When this option is activated, the output of the transmitter will be clamped to zero. Detection of empty tube conditions is by circuitry connected to extra sets of electrodes in the flowtube. The empty tube zero feature can also be activated by an external contact, such as a pump status contact.

Magmeters require five diameters of straight pipe upstream and two diameters downstream in order to maintain their accuracy and minimize liner wear. Liner protectors are available to protect the leading edge of the liners from the abrasive effects of process fluids. If the magmeter is installed in a horizontal pipe exceeding 30 ft in length, the pipe should be supported on both sides of the meter.

The magnetic flowmeter must be electrically grounded to the process liquid. This is because the magmeter is part of the path for any stray current traveling down the pipeline or through the process liquid. Bonding, by grounding the meter at both ends to the process fluid, provides a short circuit for stray currents, routing them around the flowtube instead of through it. If the system is not properly grounded, these currents can create a zero shift in the magnetic flowmeter output.

Electrical bonding to the process fluid can be achieved by metal ground straps. These straps connect each end of the flowtube to the adjacent pipeline flanges, which, in turn, are in contact with the process liquid. Straps are used when the piping is electrically conductive. When the pipe is non-conductive or lined, grounding rings are used. The grounding ring is like an orifice plate with a bore equal to the nominal size (inside diameter) of the flowtube. It is installed between the flanges of the flowtube and adjacent process piping on the upstream and downstream sides. The flowtube is bonded to the process fluid by being connected to the metallic grounding rings, and is grounded by being wired to a good conductor, such as a cold water pipe.

In larger sizes and in exotic materials, grounding rings can become expensive; grounding electrodes (a

Figure 4-5: Click on figure to enlarge.

third electrode placed in the flowtube for bonding with the process fluid) can be used instead. Another cost-saving option is to use a plastic grounding ring with a metal electrode insert.

Vortex Flowmeters

As a young person fishing in the mountain streams of the Transylvanian Alps, Theodor von Karman discovered that, when a non-streamlined object (also called a bluff body) is placed in the path of a fast-flowing stream, the fluid will alternately separate from the object on its two

downstream sides, and, as the boundary layer becomes detached and curls back on itself, the fluid forms vortices (also called whirlpools or eddies). He also noted that the distance between the vortices was constant and depended solely on the size of the rock that formed it.

On the side of the bluff body where the vortex is being formed, the fluid velocity is higher and the pressure is lower. As the vortex moves downstream, it grows in strength and size, and eventually detaches or sheds itself. This is followed by a vortex's being formed on the other side of the bluff body (Figure 4-4). The alternating vortices are spaced at equal distances.

The vortex-shedding phenomenon can be observed as wind is shed from a flagpole (which acts as a bluff body); this is what causes the regular rippling one sees in a flag. Vortices are also shed from bridge piers, pilings, offshore drilling platform supports, and tall buildings. The forces caused by the vortex-shedding phenomenon must be taken into account when designing these structures. In a closed piping system, the vortex effect is dissipated within a few pipe diameters downstream of the bluff body and causes no harm.

Vortex Meter Design

A vortex flowmeter is typically made of 316 stainless steel or Hastelloy and includes a bluff body, a vortex sensor assembly and the transmitter electronics, although the latter can also be mounted remotely (Figure 4-5). They are typically available in flange sizes from 1/2 in. to 12 in. The installed cost of vortex meters is competitive with that of orifice meters in sizes under six inches. Wafer body meters (flangeless) have the lowest cost, while flanged meters are preferred if the process fluid is hazardous or is at a high temperature.

Bluff body shapes (square, rectangular, t-shaped, trapezoidal) and dimensions have been experimented with to achieve the desired characteristics. Testing has shown that linearity, low Reynolds number limitation, and sensitivity to velocity profile distortion vary only slightly with bluff body shape. In size, the bluff body must have a width that is a large enough fraction of the pipe diameter that the entire flow participates in the shedding. Second, the bluff body must have protruding edges on the upstream face to fix the lines of flow separation, regardless of the flow rate. Third, the bluff body length in the direction of the flow must be a certain multiple of the bluff body width.

Today, the majority of vortex meters use piezoelectric or capacitance-type sensors to detect the pressure oscillation around the bluff body. These detectors

Figure 4-6: Click on figure to enlarge. (see next sheet)

respond to the pressure oscillation with a low voltage output signal which has the same frequency as the oscillation. Such sensors are modular, inexpensive, easily replaced, and can operate over a wide range of temperature ranges--from cryogenic liquids to superheated steam. Sensors can be located inside the meter body or outside. Wetted sensors are stressed directly by the vortex pressure fluctuations and are enclosed in hardened cases to withstand corrosion and erosion effects.

External sensors, typically piezoelectric strain gages, sense the vortex shedding indirectly through the force exerted on the shedder bar. External sensors are preferred on highly erosive/corrosive applications to reduce maintenance costs, while internal sensors provide better rangeability (better low flow sensitivity). They are also less sensitive to pipe vibrations. The electronics housing usually is rated explosion- and weatherproof, and contains the electronic transmitter module, termination connections, and optionally a flow-rate indicator and/or totalizer.

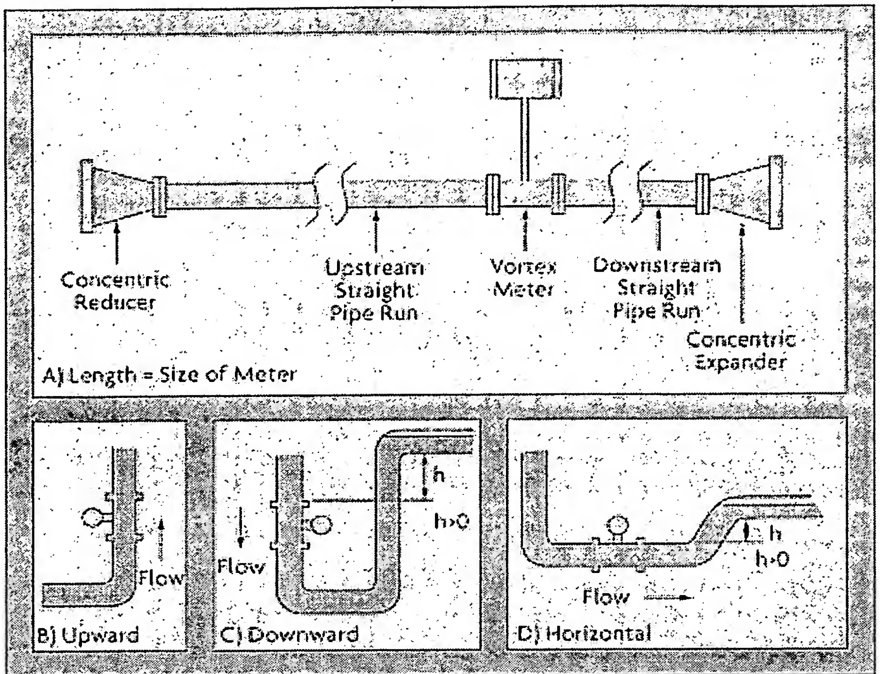


Figure 4-6: Installation Recommendations

Sizing & Rangeability

Vortex shedding frequency is directly proportional to the velocity of the fluid in the pipe, and therefore to volumetric flow rate. The shedding frequency is independent of fluid properties such as density, viscosity, conductivity, etc., except that the flow must be turbulent for vortex shedding to occur. The relationship between vortex frequency and fluid velocity is:

Where St is the Strouhal number, f is the vortex shedding frequency, d is the width of the bluff body, and V is the average fluid velocity. The value of the Strouhal number is determined experimentally, and is generally found to be constant over a wide range of Reynolds numbers. The Strouhal number represents the ratio of the interval between vortex shedding (l) and bluff body width (d), which is about six (Figure 4-4). The Strouhal number is a dimensionless calibration factor used to characterize various bluff bodies. If their Strouhal number is the same, then two different bluff bodies will perform and behave similarly.

Because the volumetric flowrate Q is the product of the average fluid velocity and of the cross-sectional area available for flow (A):

where B is the blockage factor, defined as the open area left by the bluff body divided by the full bore area of the pipe. This equation, in turn, can be rewritten as:

where K is the meter coefficient, equal to the product (A f d B). As with turbine and other frequency-producing flowmeters, the K factor can be defined as pulses per unit volume (pulses per gallon, pulses per cubic foot, etc.). Therefore, one can determine flowrate by counting the pulses per unit time. Vortex frequencies range from one to thousands of pulses per second, depending upon the flow velocity, the character of the process fluid, and the size of the meter. In gas service, frequencies are about 10 times higher than in liquid applications.

The K factor is determined by the manufacturer, usually by water calibration in a flow lab. Because the K factor is the same for liquid, gas and vapor applications, the value determined from a water calibration is valid

Figure 4-7: Click on figure to enlarge.

for any other fluid. The calibration factor (K) at moderate Reynolds numbers is not sensitive to edge sharpness or other dimensional changes that affect square-edged orifice meters.

Although vortex meter equations are relatively simple compared to those for orifice plates, there are many rules and considerations to keep in mind. Manufacturers offer free computer software for sizing, wherewith the user enters the fluid's properties (density, viscosity, and desired flow range) and the program automatically sizes the meter.

The force generated by the vortex pressure pulse is a function of fluid density multiplied by the square of fluid velocity. The requirement that there be turbulent flow and force sufficient to actuate the sensor determines the meter's rangeability. This force has to be high enough to be distinguishable from noise. For example, a typical 2-in. vortex meter has a water flow range of 12 to 230 gpm. If the density or viscosity of the fluid differs from that of water, the meter range will change.

In order to minimize measurement noise, it is important to select a meter that will adequately handle both the minimum and maximum process flows that will be measured. It is recommended that the minimum flow rate to be measured be at least twice the minimum flow rate detectable by the meter. The maximum capacity of the meter should be at least five times the anticipated maximum flowrate.

Accuracy & Rangeability

Because the Reynolds number drops as viscosity rises, vortex flowmeter rangeability suffers as the viscosity rises. The maximum viscosity limit, as a function of allowable accuracy and rangeability, is between 8 and 30 centipoises. One can expect a better than 20:1 rangeability for gas and steam service and over 10:1 for low-viscosity liquid applications if the vortex meter has been sized properly for the application.

The inaccuracy of most vortex meters is 0.5-1% of rate for Reynolds numbers over 30,000. As the Reynolds number drops, metering error increases. At Reynolds numbers less than 10,000, error can reach 10% of actual flow.

While most flowmeters continue to give some indication at near zero flows, the vortex meter is provided with a cut-off point. Below this level, the meter output is automatically clamped at zero (4 mA for analog transmitters). This cut-off point corresponds to a Reynolds number at or below 10,000. If the minimum flow that one needs to measure is at least twice the cut-off flow, this does not pose a problem. On the other hand, it can still be a drawback if low flowrate information is desired during start-up, shutdown, or other upset conditions.

Recent Developments

Smart vortex meters provide a digital output signal containing more information than just flow rate. The microprocessor in the flowmeter can automatically correct for insufficient straight pipe conditions, for differences between the bore diameter and that of the mating pipe, for thermal expansion of the bluff body, and for K-factor changes when the Reynolds number drops below 10,000.

Intelligent transmitters are also provided with diagnostic subroutines to signal component or other failures. Smart transmitters can initiate testing routines to identify problems with both the meter and with the application. These on-demand tests can also assist in ISO 9000 verification.

Some recently introduced vortex flowmeters can detect mass flow. One such design measures both the vortex frequency and the vortex pulse strength simultaneously. From these readings, the density of the process fluid can be determined and the mass flow calculated to within 2% of span.

Another newer design is provided with multiple sensors to detect not only the vortex frequency, but also the temperature and pressure of the process fluid. Based on that data, it determines both the density and the mass flow rate. This meter offers a 1.25% of rate accuracy when measuring the mass flow of liquids and a 2% of rate accuracy for gases and steam. If knowledge of process pressure and temperature is of value for other reasons, this meter provides a convenient, less costly alternative to installing separate transmitters.

Applications & Limitations

Vortex meters are not usually recommended for batching or other intermittent flow applications. This is because the dribble flow-rate setting of the batching station can fall below the meter's minimum Reynolds number limit. The smaller the total batch, the more significant the resulting

error is likely to be.

Low pressure (low density) gases do not produce a strong enough pressure pulse, especially if fluid velocities are low. Therefore, it is likely that in such services the rangeability of the meter will be poor and low flows will not be measurable. On the other hand, if reduced rangeability is acceptable and the meter is correctly sized for normal flow, the vortex flowmeter can still be considered.

If the process fluid tends to coat or build-up on the bluff body, as in sludge and slurry service, this will eventually change the meter's K factor. Vortex-shedding flowmeters are not recommended for such applications. If, however, a dirty fluid has only moderate amounts of non-coating solids, the application is likely to be acceptable. This was demonstrated by a 2-year test on a limestone slurry. At the end of the test, the K factor was found to have changed only 0.3% from the original factory calibration, although the bluff body and flowtube were badly scarred and pitted.

When measuring multi-phase flow (solid particles in gas or liquid; gas bubbles in liquid; liquid droplets in gas), vortex meter accuracy will drop

Figure 4-8: Click on figure to enlarge.

because of the meter's inability to differentiate between the phases. Wet, low-quality steam is one such application: the liquid phase should be homogeneously dispersed within the steam, and vertical flow lines should be avoided to prevent slugging. When the pipe is horizontal, the liquid phase is likely to travel on the bottom of the pipe, and therefore the inner area of the pipe should be kept open at the bottom. This can be achieved by installing the bluff body horizontally. Measurement inaccuracy in such applications is about 5% of actual flow, but with good repeatability.

The permanent pressure loss through a vortex meter is about half that of an orifice plate, roughly two velocity heads. (A velocity head is defined as V2/g, where V is the flow velocity and g is the gravitational constant in consistent units.) If the pipe and meter are properly sized and of the same size, the pressure drop is likely to be only a few psi. However, downsizing (installing a smaller-than-line-size meter) in order to increase the Reynolds can increase the head loss to more than 10 psi. One should also make sure that the vena contracta pressure does not drop below the vapor pressure of the process fluid, because that would cause cavitation. Naturally, if the back-pressure on the meter is below the vapor pressure, the process fluid will flash and the meter reading will not be meaningful.

The main advantages of vortex meters are their low sensitivity to variations in process conditions and low wear relative to orifices or turbine meters. Also, initial and maintenance costs are low. For these reasons, they have been gaining wider acceptance among users.

Installation Recommendations

When installing a vortex flowmeter in an existing process where the flow range is not known, it is recommended

Figure 4-9: Click on figure to enlarge.

to first make some approximate measurements (using portable pitot or clamp-on ultrasonic devices). Otherwise, there is no guarantee that a line-size vortex meter will work at all.

The vortex meter requires a well-developed and symmetrical flow velocity profile, free from any distortions or swirls. This necessitates the use of straight up- and downstream piping to condition the flow. The straight length of pipe must be the same size as the meter (Figure 4-6) and its length should be about the same as required for an orifice installation with a beta ratio of 0.7 (see Chapter 2). Most vortex flowmeter manufacturers recommend a minimum of 30 pipe diameters downstream of control valves, and 3 to 4 pipe diameters between the meter and downstream pressure taps. Temperature elements should be small and located 5 to 6 diameters downstream.

About half of all vortex meter installations require the "necking down" of oversized process piping by concentric reducers and expanders. Even if flow straighteners are installed, some straight (relaxation) piping will still be required.

Vortex meters can be installed vertically, horizontally, or at any angle, as long as they are kept flooded. The meter can be kept flooded by installing it in a vertical upward flow line (Figure 4-6B). When installing the flowmeter in a downward (Figure 4-6C) or horizontal (Figure 4-6D) flow, the downstream piping should be kept elevated. Check valves can be used to keep the piping full of liquid when there is no flow. Block and bypass valves are required if the replacement of the sensor in the particular design requires the stopping of the flow and the opening up of the process.

Mating flanges (on the schedule 40 or schedule 80 mating piping) must have the same diameter and smooth bore as the flowmeter. Weld neck flanges are preferred, and reducing flanges should not be used. The inner surface of the mating pipe should be free from mill scale, pits, holes, reaming scores and bumps for a distance of 4 diameters upstream and 2 diameters downstream of the meter. The bores of the meter, the gaskets and the adjacent piping must be carefully aligned to eliminate any obstructions or steps.

Excessive pipe vibration can be eliminated by supporting the piping on both sides of the meter, or by rotating the meter so that the sensor is moved out of the plane of the vibration. Process noise due to valve chattering, steam traps, or pumps can result in high readings or non-zero readings under zero-flow conditions. Most meter electronics allow for increasing the noise filter settings, but increased noise reduction usually also decreases the low-flow sensitivity of the meter. One option is to relocate the meter to a less noisy part of the process.

Ultrasonic Flowmeters

The speed at which sound propagates in a fluid is dependent on the fluid's density. If the density is constant, however, one can use the time of ultrasonic passage (or reflection) to determine the velocity of a flowing fluid.

Some manufacturers produce transducer systems that operate in the shear-mode, sending a single pulse and receiving a single pulse in return. Narrow-beam systems are commonly subject to walk-away (the signal completely missing the downstream transducer). Wide-beam systems overcome beam refraction and work better in changing liquid density and temperature. With the advent of digital signal processing, it has become possible to apply digital signal coding to the transmitted signal. This can eliminate many of the problems associated with noise and variations in liquid chemistry.

The Doppler Shift

In 1842, Christian Doppler discovered that the wavelength of sound perceived by a stationary observer appears shorter when the source is approaching and longer when the source is moving away. This shift in frequency is the basis upon which all Doppler-shift ultrasonic flowmeters work.

Doppler flowmeter transducers operate at 0.640 MHz (in clamp-on designs) and at 1.2 MHz in wetted sensor designs. The transducer sends an ultrasonic pulse or beam into the flowing stream. The sound waves are reflected back by such acoustical discontinuities as particles, entrained gas bubbles, or even by turbulence vortices (Figure 4-7A). For clamp-on designs, measurement inaccuracy ranges from ±1% to ±5% full scale (FS).

The meter detects the velocity of the discontinuities, rather than the velocity of the fluid, in calculating the flow rate. The flow velocity (V) can be determined by:

Where Ct is the velocity of sound inside the transducer, f0 is the transmission frequency, f1 is the reflected frequency, and a is the angle of the transmitter and receiver crystals with respect to the pipe axis. Because Ct /2f0cos(a) is a constant (K), the relationship can be simplified to:

Thus, flow velocity V (ft/sec) is directly proportional to the change in frequency. The flow (Q in gpm) in a pipe having a certain inside diameter (ID in inches) can be obtained by:

The presence of acoustical discontinuities is essential for the proper operation of the Doppler flowmeter. The generally accepted rule of thumb is that for proper signal reflection there be a minimum of 80-100 mg/l of solids with a particle size of +200 mesh (+75 micron). In the case of bubbles, 100-200 mg/l with diameters between +75 and +150 microns is desirable. If either the size or the concentration of the discontinuities changes, the amplitude of the reflected signal will shift, introducing errors.

Doppler flowmeters are often used to measure the flow of such fluids as

Figure 4-10: Click on figure to enlarge.

slurries. If the solids concentration is too high (in excess of 45% by weight), or if too much air or gas is entrained (especially if the bubbles are very fine), these discontinuities will attenuate the reflected Doppler signal to the point where it cannot be distinguished from the background noise in the pipe.

The reflected Doppler signal is shifted from the transmitted frequency by approximately 6 Hz for every foot per second of velocity. Therefore, if the flow velocity is less than 1 ft/sec, ultrasonic flowmetering is not practical. There seems to be no upper limit to detectable flow velocity, as successful installations at velocities in the 40-50 ft/sec range are well documented.

Transit Time Measurement

In this design, the time of flight of the ultrasonic signal is measured between two transducers--one upstream and one downstream (Figure 4-7B). The difference in elapsed time going with or against the flow determines the fluid velocity.

When the flow is zero, the time for the signal T1 to get to T2 is the same as that required to get from T2 to T1. When there is flow, the effect is to boost the speed of the signal in the downstream direction, while decreasing it in the upstream direction. The flowing velocity (Vf) can be determined by the following equation:

where K is a calibration factor for the volume and time units used, dt is the time differential between upstream and downstream transit times, and TL is the zero-flow transit time.

Theoretically, transit-time ultrasonic meters can be very accurate

Figure 4-11: Click on figure to enlarge.

(inaccuracy of ±0.1% of reading is sometimes claimed). Yet the error in these measurements is limited by both the ability of the signal processing electronics to determine the transit time and by the degree to which the sonic velocity (C) is constant. The speed of sound in the fluid is a function of both density and temperature. Therefore, both have to be compensated for. In addition, the change in sonic velocity can change the refraction angle ("a" in Figure 4-7B), which in turn will affect the distance the signal has to travel. In extreme cases, the signal might completely miss the downstream receiver. Again, this type of failure is known as walk-away.

Design Variations

Clamp-on ultrasonic meters come in either single or dual-sensor versions. In the single-sensor version, the transmit and receive crystals are potted into the same sensor body, which is clamped onto a single point of the pipe surface (Figure 4-8). In the dual-sensor version, the transmit crystal is in one sensor body, while the receive crystal is in another.

Clamp-on transit time meters have been available since the early 1970s. Their aim is to rival the performance of wetted spool-piece designs, but without the need to break the pipe or stop the process to install the meter. This goal has not yet been reached.

Clamp-on Doppler flowmeters are subject to interference from the pipe wall itself, as well as from any air space between the sensor and the wall. If the pipe wall is made of stainless steel, it might conduct the transmit signal far enough so that the returning echo will be shifted enough to interfere with the reading. There are also built-in acoustic discontinuities in concrete-lined, plastic-lined, and fiberglass-reinforced pipes. These are significant enough to either completely scatter the transmitted signal or attenuate the return signal. This dramatically decreases flowmeter accuracy (to within only ±20%), and, in most cases, clamp-on meters will not work at all if the pipe is lined.

Wetted transducer designs--both Doppler and transit time are available--overcome many of these signal attenuation limitations. The full-pipe transit-time meter originally consisted of a flanged spool section with wetted transducers mounted in the pipe wall in transducer wells opposite to one another but at 45-degree angles to the flow (Figure 4-9A). Transit-time flowmeters can be either single-path or multiple-path designs (Figure 4-9B).

Single-path flowmeters are provided with a single pair of transducers that make a single-line velocity measurement. They use a meter factor that is pre-determined by calibration to compensate for variations in velocity profile and for flow section construction irregularities.

In the design of multi-path flowmeters, several sets of transducers are placed in different paths across the flow section, thereby attempting to measure the velocity profile across the entire cross-section of the pipe. Multi-path instruments are used in large-diameter conduits, such as utility stacks, and in other applications where non-uniform flow velocity profiles exist.

Transit-time meters can also be used to measure both very hot (e.g., liquid sulfur) and very cold

(liquid nitrogen) fluids, and also to detect very low flows. Wetted-transducer designs for small pipes (down to 1/2 in.) are called axial or co-axial designs (Figure 4-10). These devices permit transit-time measurement along a path length significantly greater than the diameter of the pipe, increasing low-flow sensitivity.

Originally, ultrasonic flowmeters were divided into those using the Doppler-shift principle and those using the transit-time principle. More recently, flowmeters are capable of measuring the flow of both clean fluids and of slurries with entrained solids or other acoustical discontinuities. Microprocessors have made it possible to switch automatically from clean fluid mode to particulate mode based on the "correlation factor". This figure of merit dramatically improves the accuracy of overall performance. In some carefully engineered applications, installed accuracy to within 0.5% of reading has been reported.

Applications & Performance

Doppler flowmeters are not recommended for clean fluid applications. Transit-time flowmeters, on the other hand, are often used to measure the flow of crude oils and simple fractions in the petroleum industry. They also work well with viscous liquids, provided that the Reynolds number at minimum flow is either less than 4,000 (laminar flow) or above 10,000 (turbulent flow). Serious non-linearities are present in the transition region (Figure 4-11).

Transit-time flowmeters are the standard for measuring cryogenic liquids down to -300°C and are also used in molten metal flowmetering. Measurement of liquid argon, liquid nitrogen, liquid helium and molten sulfur have often been reported. Spool-section type flowmeters are most often used for these applications, especially the axial and co-axial designs.

Raw wastewater applications usually have too few acoustic discontinuities for Doppler flowmeters. On the other hand, raw wastewater is not clean enough all the time for transit-time measurement. Other wastewater-related applications are equally problematic, as the solids concentration can be too high for either transit-time or Doppler flowmeters to work properly. In still other wastewater applications, the problem is that the acoustical absorbency of the mostly organic solids in wastewater attenuates the ultrasonic signals.

The use of multi-path flowmeters in raw wastewater and storm water applications is common, while Doppler or cross-correlation hybrid designs are most often used to measure activated sludge and digested sludge flows.

For mining slurries, Doppler flowmeters typically work well. Among the few problem applications are those in HDPE pipe, because the pipe wall flexes enough to change the diameter of the measurement area. This affects the accuracy of the meter. In addition, the flexure of the pipe wall can often break the acoustic coupling of the transducer to the outside of the pipe, causing failure. Another problem area is the measurement of slurries that are acoustically absorbent, such as lime or kaolin slurries. These applications fail because the highly absorbent solids attenuate the signal below usable strength. Lower frequency (0.45 MHz) sensors have been tried for these applications, but success has been limited.

Multi-path, transit-time flowmeters also measure stack gas flows in power-plant scrubbers, even in very large diameter stacks.

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